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Water Vaporization From Heated Tissue: An In Vitro Study by Differential Scanning Calorimetry

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Background and Objective: **The heat balance equation is central to modeling laser vaporization of tissue. Because about 70% of tissue is water, energy loss due to water vaporization becomes an important consideration in modeling. In this study, the rate and pattern of water vaporization from various animal tissues studied by differential scanning calorimetry (DSC) are reported.**
Study Design/Materials and Methods: **DSC thermograms of fresh muscle, liver, and kidney tissues were made at heating rates of 2°C/min, 5°C/min, and 10°C/min in the temperature range of 30–150°C. Thermograms of vacuum-dried muscle sample were also made to establish that the endotherms obtained were essentially due to the water in the tissue.**
Results and Conclusion: **Two broad peaks—one below and the other above 100°C—are seen in all the endotherms. The peaks are attributed to the structural and compositional features of tissue and tissue water. The two-stage vaporization pattern has importance in modeling tissue heating by a continuous-wave Nd:YAG laser.**

Key words: laser, tissue, endotherm, latent heat of vaporization, photothermal models

INTRODUCTION

Quantitative knowledge of tissue vaporization is important in the optimization of laser procedures and in developing new applications. Laser–tissue interaction models suitable for surgical application invariably center around the heat balance in which heat generated by the absorption of the laser beam by tissue and heat lost due to various mechanisms, such as conduction, convection, and radiation, are to be considered [1–4]. In addition, in the tissue vaporization process, the heat lost due to mass loss is also to be taken into account. Because, approximately 70% of tissue is water and the latent heat of vaporization of water is very high, the heat loss due to vaporization of water is large compared with other pathways. This assumption is still valid even if the reduction of latent heat of vaporization of tissue water in laser ablation processes, presumably due to transient pressure effects [5], are taken into account. It is thus important to know the rate and pattern of water vaporization from tissue in developing laser–tissue interaction models. This paper reports a study of this subject that used differential scanning calorimetry (DSC).

MATERIALS AND METHODS

Skeletal muscle, liver, and kidney tissue obtained from freshly sacrificed New Zealand White rabbits were used for the experiments. A Dupont model 990 thermal analyzer, in conjunction with a model 910 DSC cell, was used to record thermograms taken at a heating rate of 5°C/min in the temperature range of 30–150°C. The thermograms were also taken at heating rates of 2°C/min and 10°C/min to determine the effect of the rate of heating on the water vaporization pattern. Thermograms for muscle tissue, vacuum dried at 30°C for 2 hr, were made to establish that the endotherms obtained were essentially caused by water in the tissue. The quantity of water vaporized was estimated by taking the weight of the sample before and after each DSC run. The change in weight due to vacuum drying was also noted in the three cases.

RESULTS

Typical thermograms for muscle, liver, and kidney tissue are shown in Figures 1–3. The thermogram for muscle tissue shows two distinct peaks, corresponding to endothermic transitions centered at 92°C and 111°C (Fig. 1a). The vacuum-dried muscle tissue sample, however, showed no peaks (Fig. 1b). The curve for both liver and kidney tissue also showed two peaks, centered at 84°C and 113°C, and at 82°C and 114°C, respectively (Figs. 2 and 3). In all cases, no

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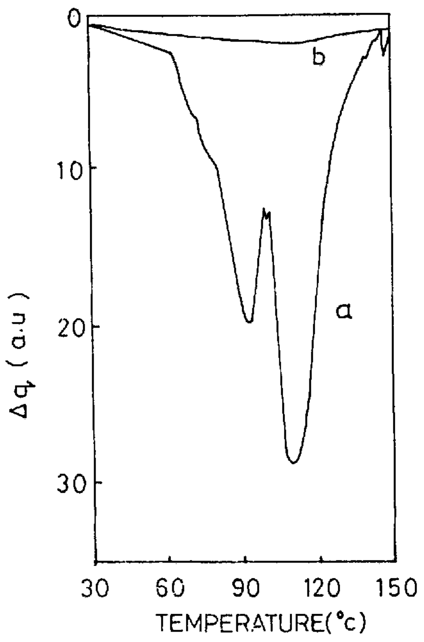

Fig. 1. DSC thermograms for fresh (a) and vacuum-dried (b) muscle tissue. Heating rate is 5°C/min.

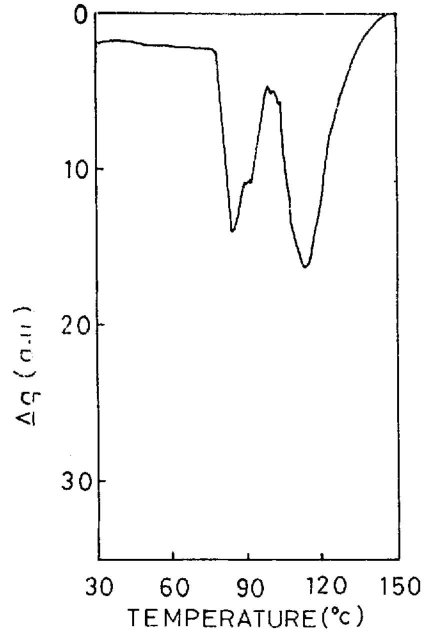

Fig. 2. DSC thermogram for liver tissue. Heating rate is 5°C/min.

appreciable difference was observed when the heating rate was set at 2°C/min and 10°C/min.

The change in weight of the tissue sample caused by heating in the DSC run corresponds well with the change in weight caused by vacuum drying, and both agree with the reported values of the percentage of water in rabbit tissue (Table 1). Further, the thermogram for the vacuum-dried sample does not have a phase-transition pattern, indicating that the broad peaks in the endotherm for fresh samples are due to the presence of water. Because the heat of vaporization of water is considerably higher than the specific heat, it can be assumed that the DSC curves represent the approximate rate of vaporization of water from tissue.

Two temperature bands can be identified in the curves. In the case of muscle tissue, the first band is between 30°C and 101°C, where a rapid increase in vaporization occurs above 65°C, with a maximum at about 92°C. The second is between 101°C and 150°C, with the maximum at 111°C. For both liver and kidney tissue, the corresponding bands are 30–104°C and 104–150°C, respectively. The area confined by the curve in each band gives the relative amount of tissue water vaporized in the respective temperature bands. Table 2 shows the percentage of water vaporized in the two temperature bands in each type of tissue. In all tissues studied, about 50% of the total water is vaporized only after attaining temperatures well above 100°C, and the effect is predominant in muscle tissue.

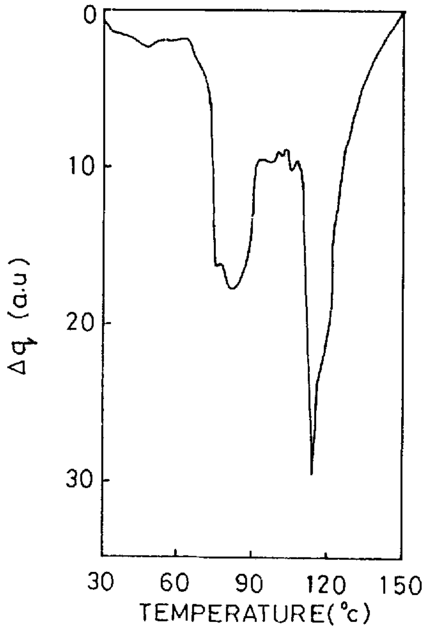

Fig. 3. DSC thermogram for kidney tissue. Heating rate is 5°C/min.

DISCUSSION

To the best of our knowledge, two-stage vaporization of water in tissue, as indicated by the

TABLE 1. Reduction in Weight of Rabbit Tissue Samples After DSC Run and After Vacuum Drying Compared With Reported Values of Water Percentage in Tissue

	% reduction in weight		% of water as reported in Duck [6]
Tissue	After DSC run	After vacuum drying	
Muscle	76.0	75.2	77–80
Liver	72.8	72.0	70–76
Kidney	77.1	76.5	74–79

Complete vaporization of water is evident in the DSC run at 30–150°C.

TABLE 2. Approximate Percentage of Water Vaporized in the Two Temperature Bands Obtained From the DSC Curve

	1st band		2nd band	
Tissue	Temperature range (°C)	% of water vaporized	Temperature range (°C)	% of water vaporized
Muscle	30–101	44	101–150	56
Liver	30–104	51	104–150	49
Kidney	30–104	50.2	104–150	49.8

two peaks in the endotherm, has not been reported thus far. The presence of the two peaks may be attributed to the structural and compositional features of tissue and tissue water. The structure of tissue water has been studied widely for applications in magnetic resonance imaging. The translational coefficient of tissue water determined by nuclear magnetic resonance (nmr) pulsed gradient studies was found to be about one half of the pure water value [7]. The widely accepted explanation for this behavior is that the tissue water behaves as if it has two phases—one free and the other bound to the macromolecules [8]. The fact that a certain fraction of tissue water remains unfrozen at a temperature substantially below 0°C is a further indication of the existence of the two phases [9,10]. The two peaks in the DSC endotherm may represent vaporization of these two phases. The tissue-to-tissue changes in the positions of the peaks and the percentage of water vaporized in each band (Table 2) indicate that the structural aspects of tissue also contribute to the two-step process. Further studies are in progress to gain deeper insight into this interesting phenomenon.

When a continuous wave Nd:YAG laser is used for tissue vaporization, the adjacent areas of the ablated zone encounter relatively low heating rates. Furthermore, in applications such as laser coagulation and laserthermia, the heating rate is low. It may be inferred from the present observations that in such situations the endothermic changes related to water evaporation take away a large amount of heat and this happens predominantly in two stages. This aspect has a bearing on developing the corresponding photothermal models. However, further experiments are necessary to extend the phenomena to faster laser ablation processes.

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